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Final Technical Report

Effects of Bottom Topography on Ocean General Circulation

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1. Introduction

The long-range objective of the P.I. is to understand the motion of deep waters throughout the abyssal basins of the world ocean, both along the boundaries and over the abyssal plains. The zeroth-order theory of the spread of the deep water was presented in a classical paper by Stommel and Arons (1960), which assumed uniform upwelling of the bottom water above a flat-bottomed ocean. However, the real ocean floor displays rich variations in topography from isolated seamounts to the global system of mid-ocean ridges. These topographic features guide and sometimes prevent the movement of deep waters, thereby controlling the general circulation. Also, superimposed on the large-scale, thermohaline upwelling circulation are the local wind-driven circulation which can penetrate to the ocean bottom in such regions as the recirculation gyres of the mid-latitudes and the Antarctic Circumpolar Current region.

The aim of this project was to understand the effect of bottom topography on the abyssal circulation of the world ocean from a theoretical angle. Analytical, simple numerical and laboratory models were employed for this purpose. The abyssal layer of the ocean was studied in isolation from the upper layer. Focus was on the role of large-scale bottom features such as mid-ocean ridges and abyssal basins in guiding the pathways of the abyssal circulation driven by deep water production and upwelling processes. As such, this work can be regarded as elaborations on the classical Stommel-Arons model of the abyssal circulation.

The situations studied were all idealized ones, the intent being that fundamental aspects of the behavior of the abyssal fluid be revealed, except one case in which, though

still idealized, an attempt was made to simulate the circulation in deep western tropical Atlantic. The principal result of this study was a successful extension of the Stommel-Arons model to cases with bottom topography which also revealed that the fundamental vorticity balance that governs the Stommel–Arons model will not hold in certain regions of the abyssal ocean.

2. Theoretical and Numerical Investigations

Smallness of internal deformation radius in the ocean indicates that the leading order features of the large scale ocean circulation can be modelled under the planetary geostrophic approximation, which assumes strict geostrophy and hydrostacy for the momentum equations but retains full nonlinearity in the thermodynamic or, in the case of a layer model, mass continuity equation. When forcing and friction are absent, a single layer fluid parcel obeying the planetary geostrophic dynamics conserves a potential vorticity of the form f/H, where $f \equiv 2\Omega \sin\theta$ is the Coriolis parameter (Ω is the angular velocity of the earth's rotation and θ is the latitude) and H the thickness of the fluid layer. Isopleths of f/H are called *geostrophic contours*, and in the absence of forcing and friction the flow is expected to follow geostrophic contours. This conservation law is the primary constraint on the fluid flow in the abyss. When forcing and friction are present, f/H is no longer conserved, but its rate of change can be related straightforwardly to the effect of forcing and friction.

Large-scale topography exercise a strong control on the flow by influencing the fluid thickness H and defining the primary patterns of geostrophic contours. On those geostrophic contours that terminate on the lateral boundaries of the ocean, free flow along the contour is not possible since it would eventually be blocked by the boundary. Such contours are thus called *blocked*. Only forced flow with a finite velocity component perpendicular to the contour will be possible. On the other hand, a contour that form a loop (called *closed* contours) can have a free flow along it in the absence of friction. Closed contours can be formed around prominent topographic maxima or minima (Figure 1).

As a first step in investigating such a constraint on the abyssal circulation, spin-up of circulation driven by an inflow into an abyssal basin containing a simple large-scale topographic feature was studied using an inverted one-and-a-half layer shallow water

model. This work has been reported in a published paper (Kawase and Straub, 1991). Two types of topography, one a plateau and the other a depression, were considered. In both cases, the topography gives rise to a region of closed geostrophic contours. As might be expected, the character of the adjustment and the resultant flow were found to differ markedly between the closed geostrophic contour region and the region outside. Long wave processes set up a modified Stommel–Arons flow outside the closed contour region, while inside the closed contour region a vigorous recirculation is generated whose magnitude is eventually limited by friction (Figure 2). It was shown that the ratio of the velocity of the recirculation to that of the Stommel–Arons flow is of the order of the ratio of the radius of the closed contour region to the Stommel boundary layer thickness. This means that, in the realistic parameter range of small friction giving rise to currents with western intensification, there can be a recirculation of substantial magnitude in the closed contour region. Moreover, it was shown that the recirculation inside the closed contour region is always cyclonic, whether the topography is a plateau or a depression (Figure 3). This is because the sense of the circulation is dictated by the sign of the vorticity input, which comes from stretching of f due to upwelling and thus is always cyclonic, not by the sign of topography. The sign of the topography does, however, dictate the formation of meanders in the flow around the rim of the closed contour region. In the plateau case, the combined topographic and planetary beta effect gives rise to an anticyclonic phase propagation of Rossby waves, which can be arrested by the cyclonic mean flow to form meanders. In the depression case, the direction of Rossby wave propagation and mean flow are the same and no stationary wave can be expected.

This work led to a speculation that, in an isolated mid-latitude abyssal basin, the character of the circulation might be more of a basinwide recirculation rather than a slow interior flow compensated by a western boundary current as suggested by the Stommel–Arons model. Accordingly, simple numerical experiments were performed to investigate the bottom water circulation pattern in a bowl-shaped, or a concave, abyssal basin driven by the inflow–upwelling process. This work has been summarized in a note which is presently in press in *Journal of Physical Oceanography* (Kawase, 1992a). In a basin wholly contained in one hemisphere, the concave bottom geometry introduces a strong topographic

beta effect around the rim of the basin, and the character of the circulation is indeed fundamentally altered from the circulation pattern in a flat bottom basin, where a sluggish northeastward interior flow is compensated by a strong western boundary current, to a basinwide cyclonic recirculation of a substantially greater strength without western intensification (Figure 4). In contrast, circulation in a similar basin that straddles the equator fails to show a significant difference from the circulation in a flat bottom basin (Figure 5). This dichotomy between an equatorial and a mid-latitude basins can be understood in terms of the geometry of the underlying geostrophic contours. In mid-latitude basins, a substantial portion of geostrophic contours do closed to allow recirculatory flows. In an equatorial basin, because of sign change of f, such closure does not occur and contours remain blocked. While at present observations of the abyssal circulation are not extensive enough to test whether or not such a dichotomy exists in the earth's ocean, it gives rise to a strong possibility that the Stommel–Arons dynamics may not apply in all abyssal basins.

As an application of insights gained from these investigations, simple analytical and numerical models of the abyssal circulation were used to explore the possibility, first suggested by Warren (1981), that the northward deepening of the sea floor in the western basin of the tropical North Atlantic Ocean is responsible for the observed eastward confinement of the Antarctic Bottom Water current, a result contrary to what the Stommel–Arons model predicts. This work has been summarized in a paper submitted to *Deep-Sea Research* (Kawase, 1992b, accepted subject to revision at the time of writing). The models were configured simply to have a downward ramp of sea floor starting from just north of the equator up to 25°N, which replicates the gross feature of the western Atlantic bottom topography (Figure 6). It was shown that (a) a topographic slope of magnitude observed in this region of the Atlantic forces separation of the northward–flowing deep western boundary current at a low latitude, (b) north of this latitude the circulation is dominated by a large–scale cyclonic gyre extending up to where the sea floor becomes flat again, with a northward flow along the eastern boundary as a part of it and a westward flow at about 25°N. A circulation pattern from the standard case is shown in Figure 7. Because of this basinwide cyclonic gyre, newly entering waters into the North Atlantic from the south is confined to a narrow region adjacent to the eastern boundary, as revealed by simulated

float tracks (Figure 8). These results were robust under variation of topographic, forcing and frictional parameters, although quantitative aspects and details were sensitive to such variations. Eastward flow through Vema Fracture Zone, recently estimated by McCartney et al. (1991) to be about 2Sv, will divert some of the northward-flowing eastern boundary current, but otherwise does not affect the circulation. These results compare favorably with recent observations that report southeastward flow along the western boundary at least down to 8°N and suggest a recirculation of abyssal water in this region (Molinari, *et al.*,, Johns, *et al.*). Further, the model predicts that the extent of the cyclonic gyre, and therefore the eastward confinement of the new water, will be limited to the south of 25°N where the floor becomes flat again. This aspect of the circulation, which has not been previously modelled, again agrees with the observations that suggest a northern limit of the Antarctic Bottom Water flow along the eastern boundary at this latitude and a possible westward separation there (Metcalf, 1969).

We also explored the possibility of studying the mesoscale, as opposed to the basinwide scale, behavior of bottom water masses, in particular bottom-trapped eddies and filaments. Under the P.I.'s guidance, Dexing Wu, a graduate student, developed a particle-in-cell model of abyssal layer which is designed to study the mesoscale behavior of abyssal water masses. This approach seems to hold a great deal of promise for a detailed study of abyssal water mass behavior. For instance, we studied the interaction of an abyssal eddy with the ambient fluid by overlaying a one or two layer quasi-geostrophic model representing the latter. The movement of the abyssal eddy along an isobath excites topographic Rossby waves in the ambient fluid, which exerts a drag on the eddy and causes the eddy to fall downslope. Energetically, this amounts to conversion of available potential energy stored in the form of the eddy's upslope position into kinetic energy of the wave in the upper layer. This process is energetically analogous to baroclinic instability in a two-layer fluid, which can also be interpreted as interfacial form drag applied to the shear between the two layers. He also studied interaction of migrating bottom-trapped eddies with large scale topography, and showed that an eddy drifting around a large scale isolated topography can be sheared out and broken up irreversibly. Unfortunately, Wu failed to perform satisfactorily in his general examination and his study was therefore terminated.

3. Laboratory Investigations

Because of difficulties in observing the abyssal ocean, it is difficult to test the validity of the model results directly against observations. Thus laboratory experiments become important alternative methods of investigating fluid behavior in the parameter range of abyssal flow. Numerical and laboratory experiments can be compared with and checked against each other to reveal their similarities and differences, which will give us some idea of robustness of the results and limitations of each approach.

During the period of this grand we hosted Dr. Scott Condie, a UCAR Ocean Modelling postdoctoral fellow, with whom the P.I. collaborated in laboratory experiments to test some of the ideas described above. In particular, we studied source driven flows in a laboratory tank system consisting of two basins (with sloping sidewalls) separated by a mid-ocean ridge, and compared the results with those from a numerical model configured to simulate the laboratory situation. This work is described in a paper in press in the *Journal of Marine Research* (Condie and Kawase, 1992). Numerical spin-up occurs via topographically modified Kelvin waves which propagate away from the source region around the outer perimeter of the model ocean. Energy is then carried along the ridge by topographic waves and westward by planetary waves. The resulting flow eventually concentrates in strong cyclonic circulation patterns, defined by regions of closed geostrophic contours in the lower latitude portion of each basin, as expected from previous results. A surprising aspect of this model's behavior, however, was that the circulation pattern was strongly affected by the location of the source. When the deep water source is located at the latitude of closed geostrophic contours, there is no significant flow outside the closed contours (Figure 9). However, when it is located further toward polar regions, strong flow is evident up to the source latitude (Figure 10). This location dependence was replicated in the laboratory model, whose large scale behavior agreed well with the numerical model when similarity conditions were satisfied. One notable difference, however, was a higher level of wave and eddy activity in the laboratory, particularly near the border between closed and blocked contour regions. This variability seems attributable to the significant lateral friction from molecular viscosity, and consequent lateral boundary layers, in the laboratory tank.

4. Conclusion

Theoretical studies of the abyssal circulation had long been a neglected topic since the publication of the original Stommel–Arons paper. Thus much work at a fundamental level had to be (and still remains to be) done. The present work has addressed the problem at its simplest level, namely a single layer of abyssal water under a stagnant water above, guided by large scale (both in horizontal and vertical) topography. As such this work should serve as a building block for a more complete theory which ought to include (1) a more complex stratification, consisting of multiple layers or a continuous variation, (2) smaller scale topographic features which might provide dissipative mechanisms, and (3) influence of the upper layer both in terms of mean flow and eddy activities.

5. Publications

Kawase, M. and D. Straub, 1991: Spinup of source–driven circulation in an abyssal basin in the presence of bottom topography: *Journal of Physical Oceanography*, **21**, 1501–1514.

Kawase, M., 1992a, Effects of a concave bottom geometry on the upwelling-driven circulation in an abyssal ocean basin, *Journal of Physical Oceanography*, in press.

Condie, S.A., and M. Kawase, 1992, Models of abyssal flow in basins separated by a mid-ocean ridge, *Journal of Marine Research*, in press.

Kawase, M., 1992b, Topographic effects on the bottom water circulation of the western tropical North Atlantic Ocean, submitted to *Deep-Sea Research.*

6. References (other than those cited above)

Johns, W.E., D.M. Fratantoni and R.J. Zantopp, 1991: Deep Western Current Variability off Northeastern Brazil. Submitted to *Deep-Sea Res.*.

McCartney, M.S., S.L. Bennett and M.E. Woodgate-Jones, 1991: Eastward flow through the Mid-Atlantic Ridge at 11°N and its influence on the abyss of the Eastern Basin. *J. Phys. Oceanogr.*, **21**, 1089–1121.

Metcalf, W.G., 1969: Dissolved silicate in the deep North Atlantic. *Deep-Sea Res.*, **16** (supplement), 139–145.

Molinari, R., R. A. Fine, and E. Johns, 1991: The deep western boundary current in the tropical North Atlantic Ocean. Submitted to *Deep-Sea Res.*.

Stommel, H., and A.B. Arons, 1960: On the abyssal circulation of the world ocean — I. Stationary planetary patterns on a sphere. *Deep-Sea Res.*, **6**, 140–154.

Warren, B.A., 1981: Deep circulation of the world ocean. In: *Evolution of Physical Oceanography, Scientific Surveys in Honor of Henry Stommel*, B.A. Warren and C. Wunsch, editors, MIT Press, Cambridge, Massachusetts, pp. 6–41.

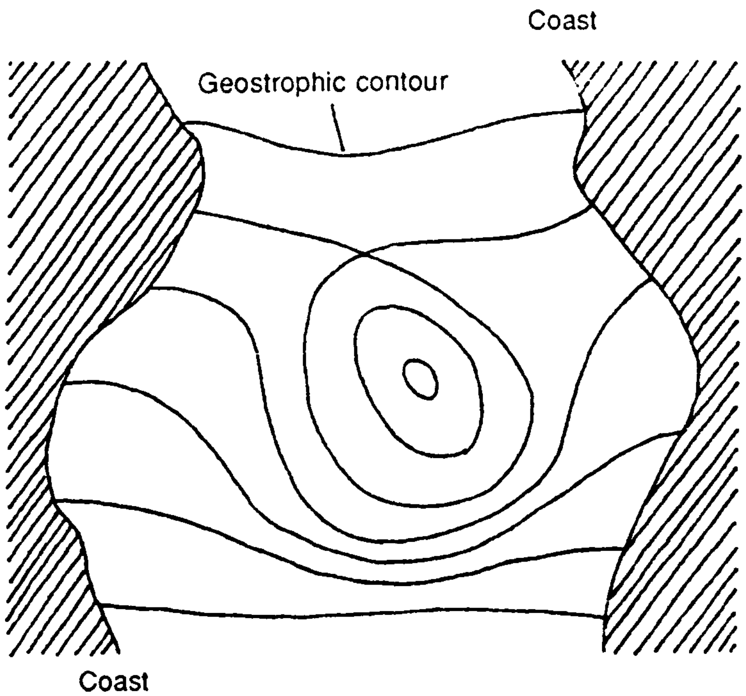

Figure 1. Schematic picture of closed and blocked geostrophic contours as would be created by a large scale. isolated positive bottom topography (a plateau) in the northern hemisphere.

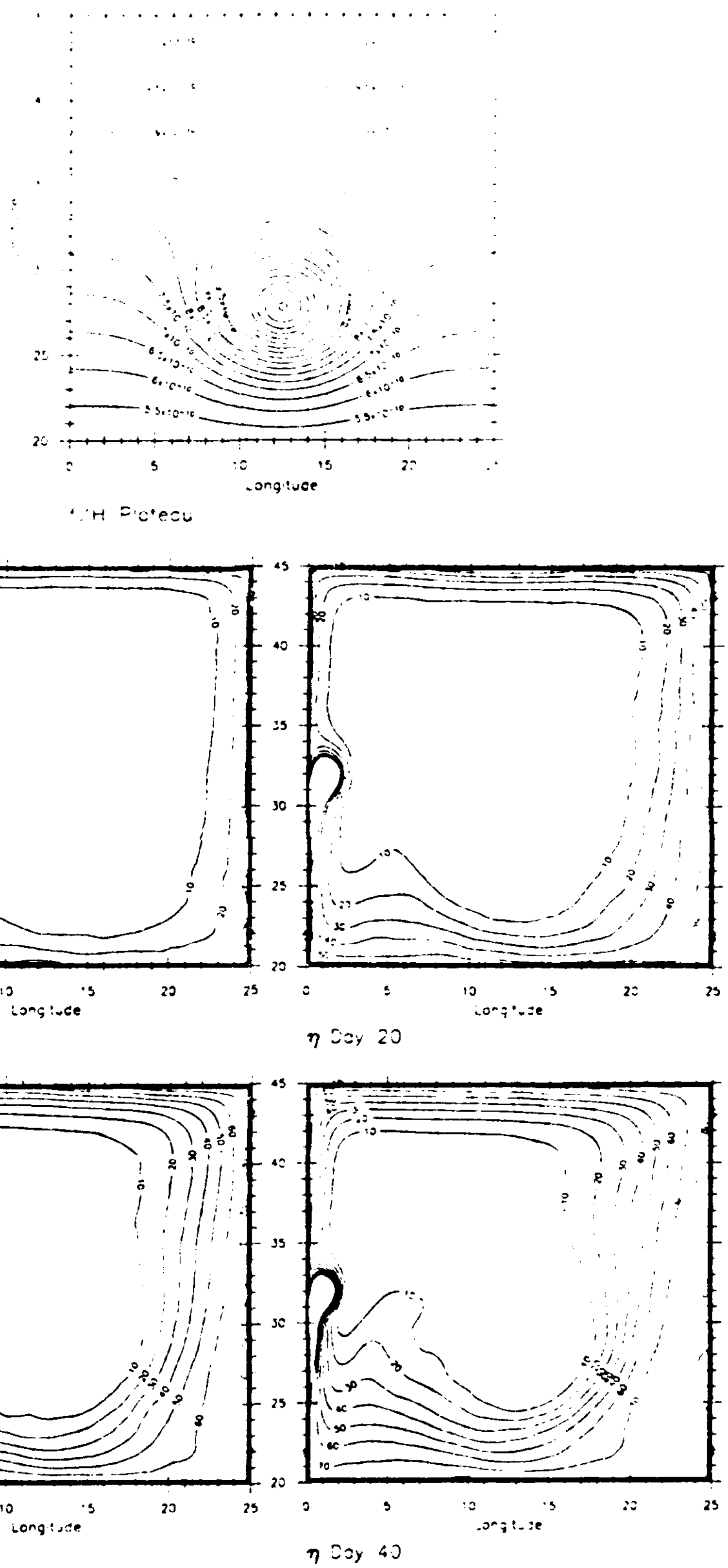

Figure 2. Geostrophic contours (f/H, in (cm sec)$^{-1}$) and spin-up of circulation in an abyssal basin with a plateau in the middle during the first forty days, shown in terms of interface elevation η (in centimeters) which is proportional to the pressure in the abyssal layer. Geostrophic currents are parallel to the isopleths of η. From Kawase and Straub (1991).

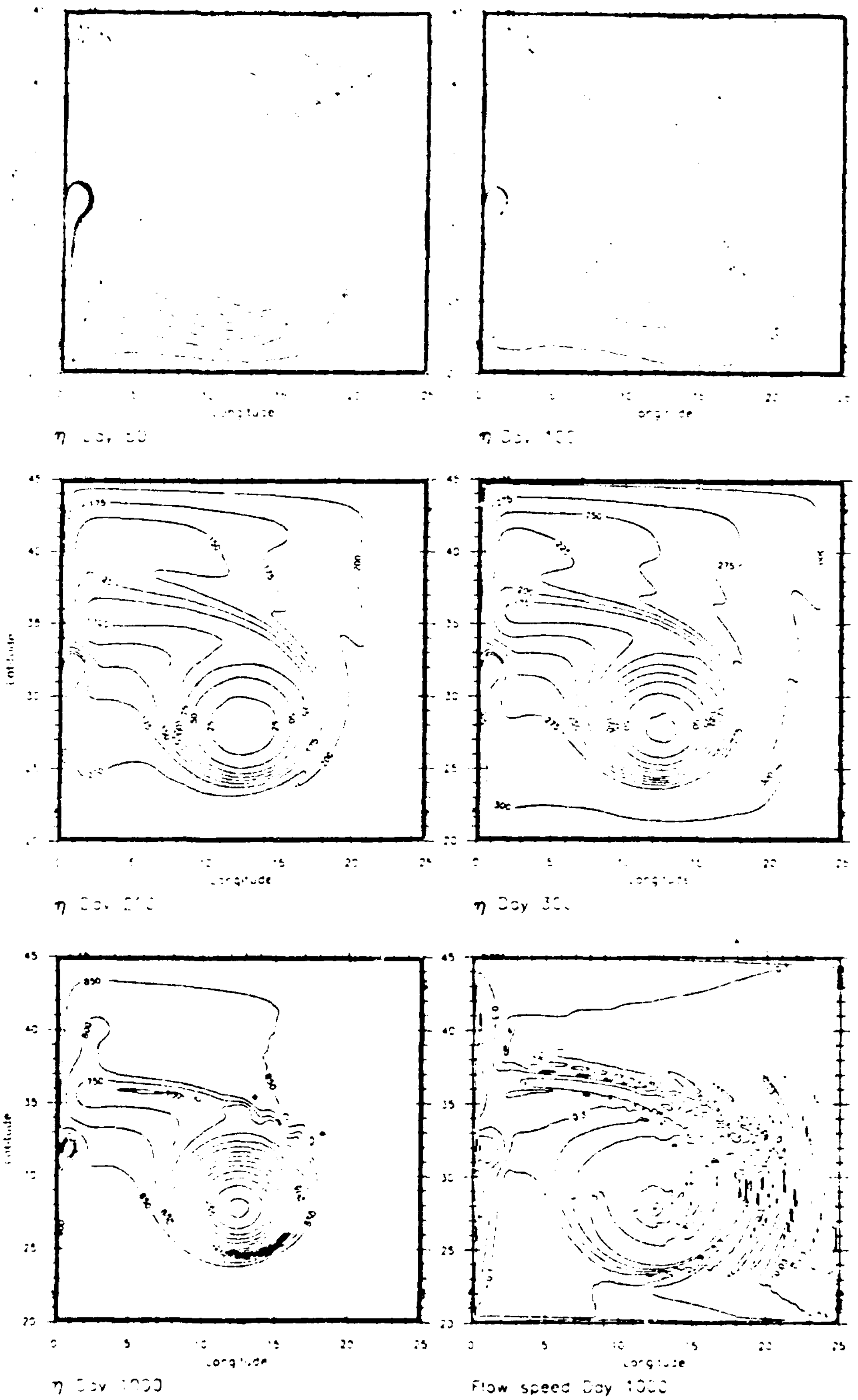

Figure 2 (continued) Spin up to Day 300 and the mature flow on Day 1000 in terms of η and flow speed (in cm/sec). From Kawase and Straub (1991).

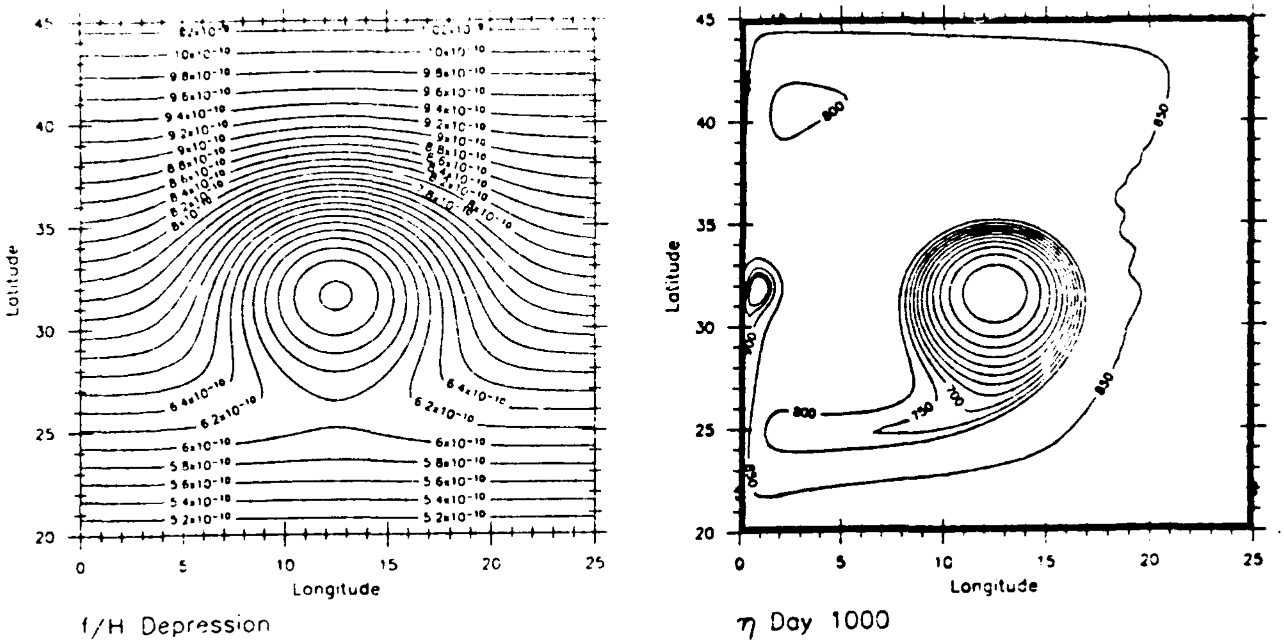

Figure 3. f/H (in (cm sec)$^{-1}$) and the mature flow on Day 1000 in terms of interface elevation η (in centimeters) for the circulation in an abyssal basin with a depression in the middle, showing that the circulation that develops over the closed contour region is still cyclonic. From Kawase and Straub (1991).

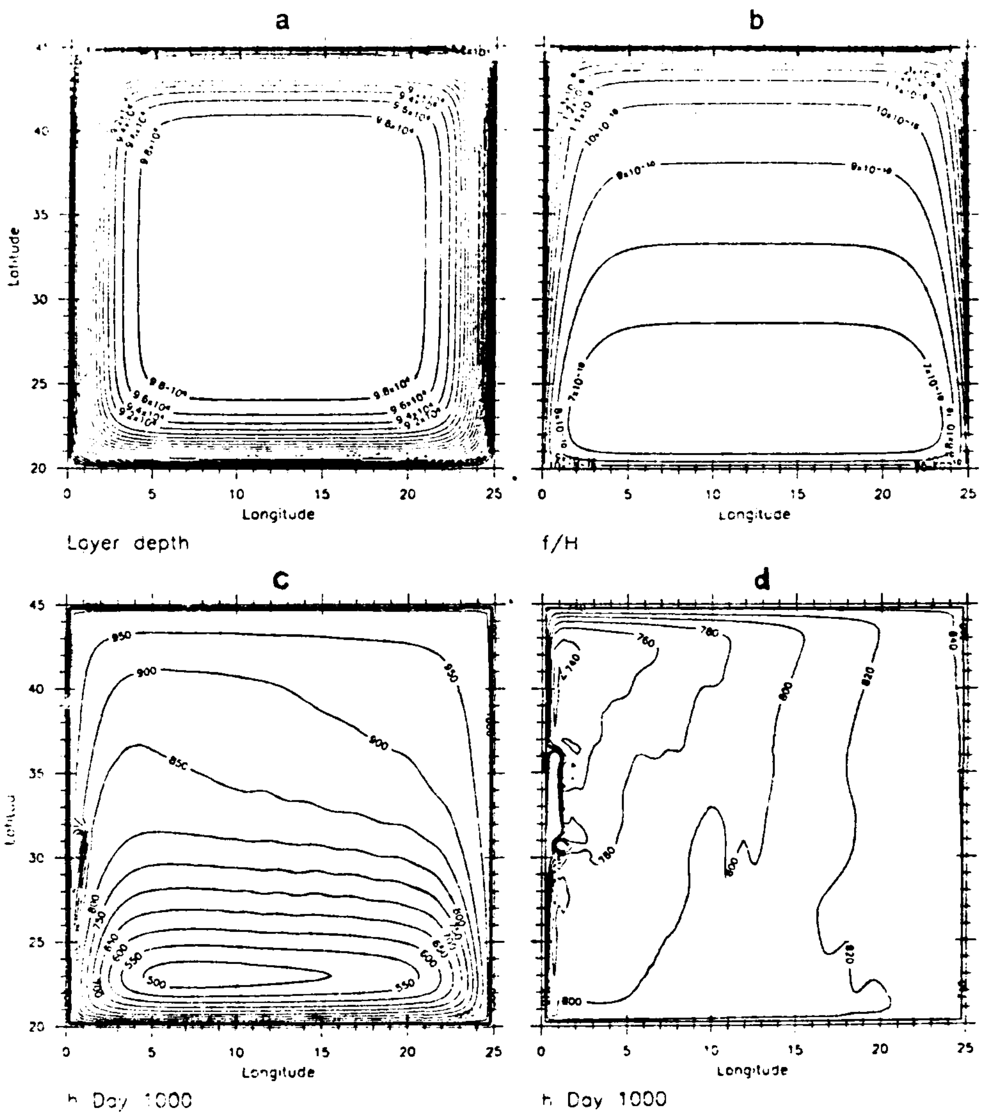

Figure 4. (a) Undisturbed layer depth (in centimeters), (b) geostrophic contours (f/H, in (cm sec)$^{-1}$), (c) interface elevation on Day 1000 (in centimeters) showing basinwide recirculation and (d) interface elevation on Day 1000 for a corresponding flat-bottom calculation showing the Stommel-Arons circulation pattern. Note that the contour interval for (c) is 500cm while for (d) it is 200cm. From Kawase (1992a).

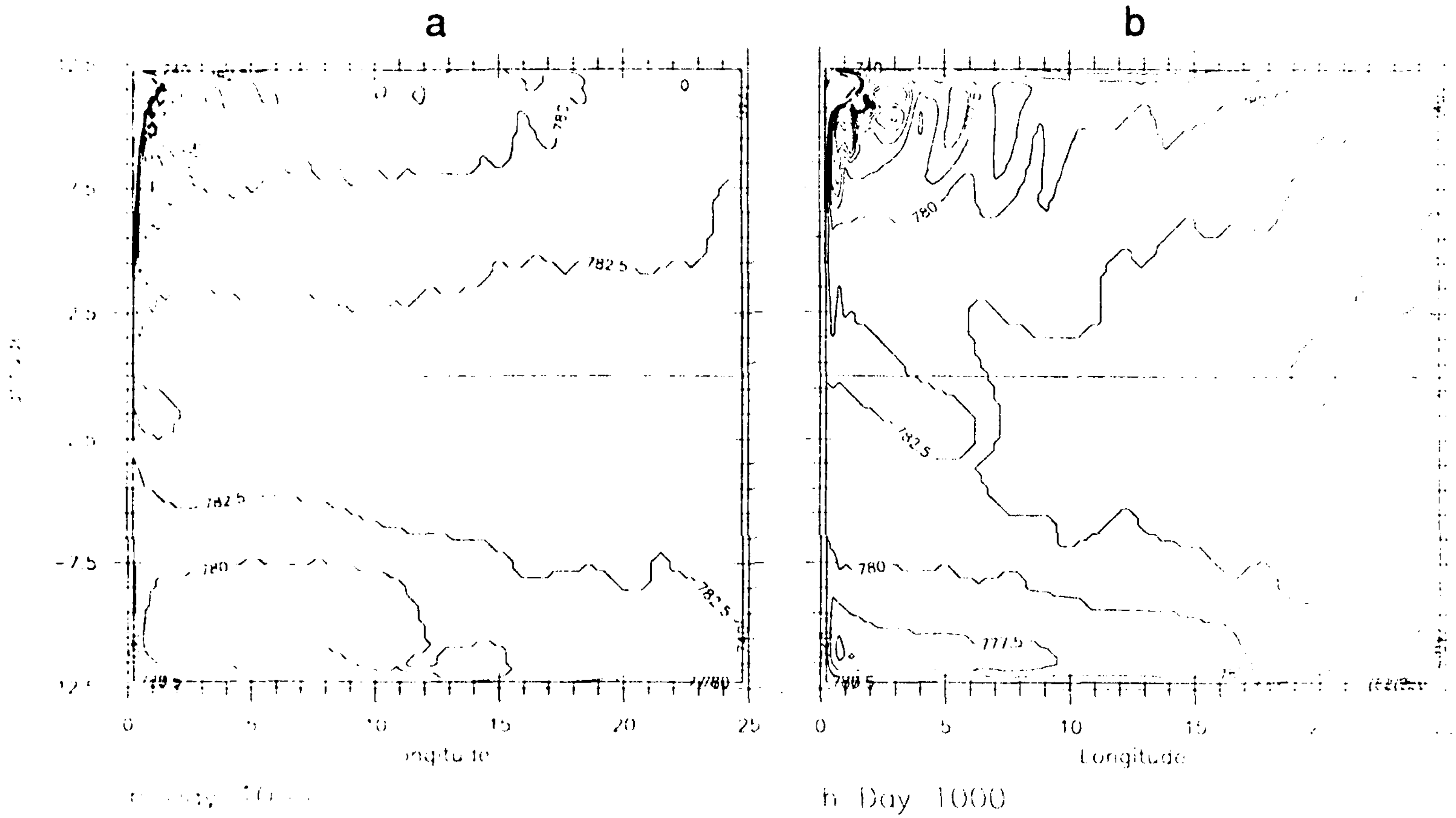

Figure 5. (a) Interface elevation on Day 1000 (in centimeters) for a basin with the same geometry as Figure 4(a) but centered on the equator. (b) interface elevation on Day 1000 for a corresponding flat bottom calculation. From Kawase (1992a).

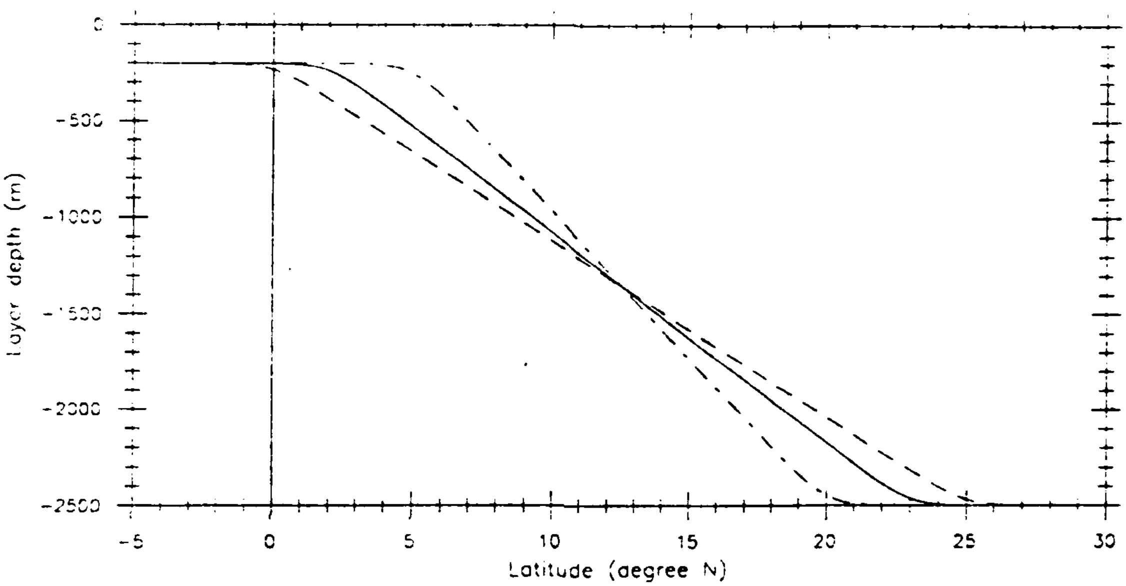

Figure 6. Undisturbed layer depths (in meters) as a function of latitude for the idealized model of the abyssal western North Atlantic Ocean. Three different slopes — one with a normal f/H gradient, one neutral (standard case), and the other a reversed gradient — are shown, all however developing a cyclonic recirculation in the slope region. From Kawase (1992b).

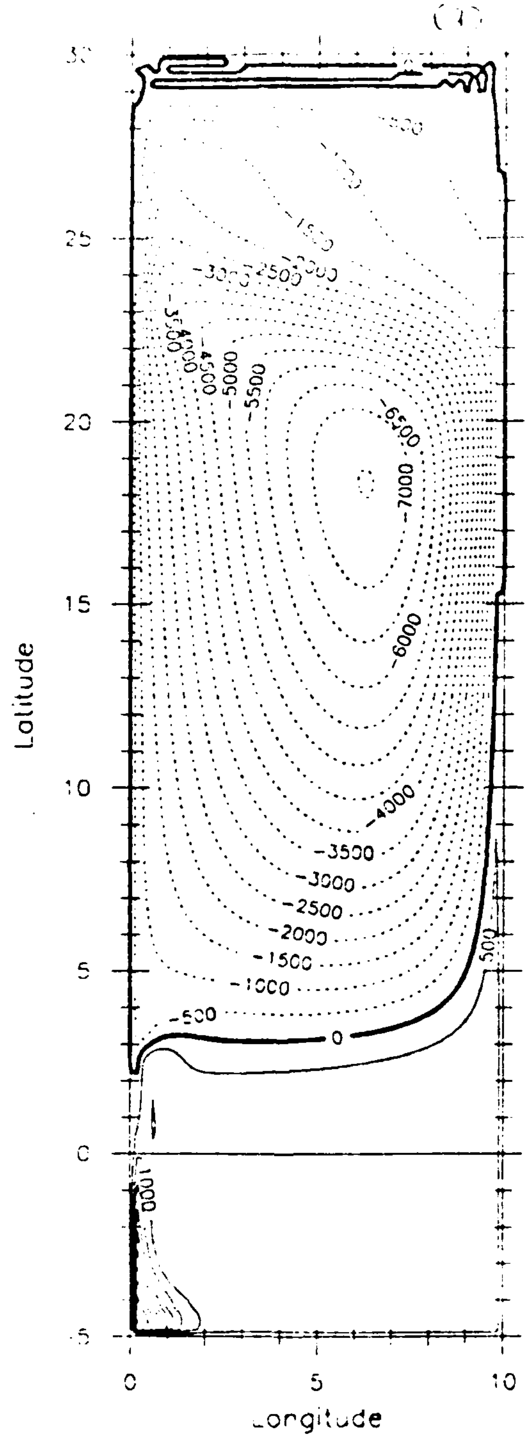

Figure 7. Circulation in the idealized model of the abyssal western North Atlantic Ocean for the standard case in terms of interface elevation η (in centimeters). From Kawase (1992b).

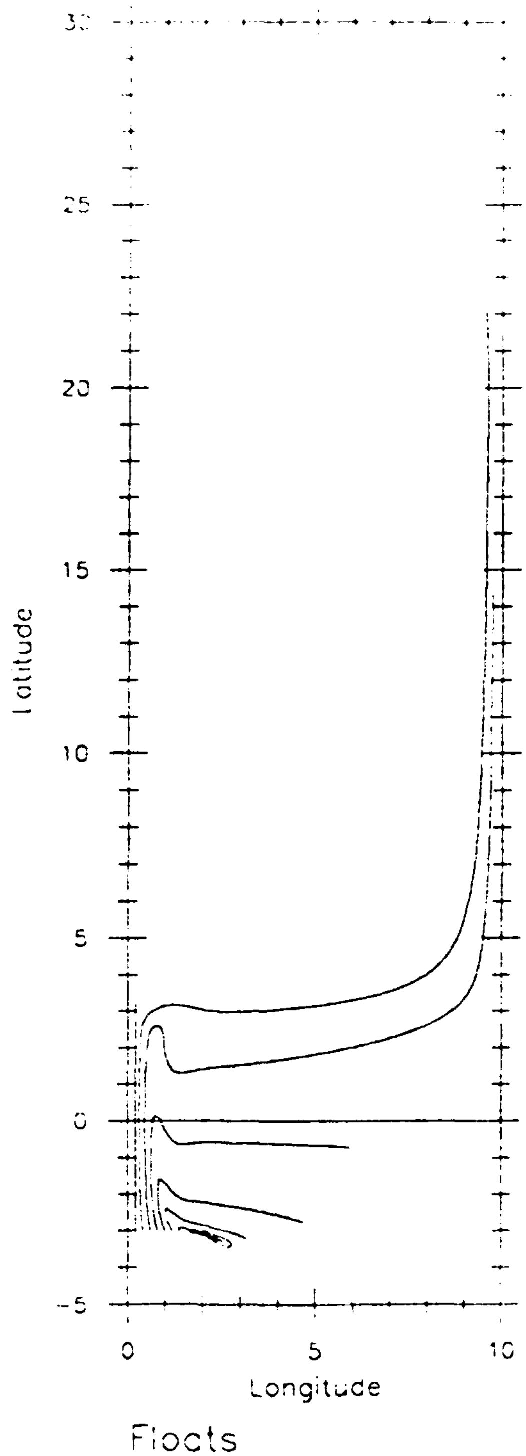

Figure 8. Simulated tracks of ten floats released at 3°S in the western boundary current in the circulation depicted in Figure 7 over 4000 days. From Kawase (1992b).

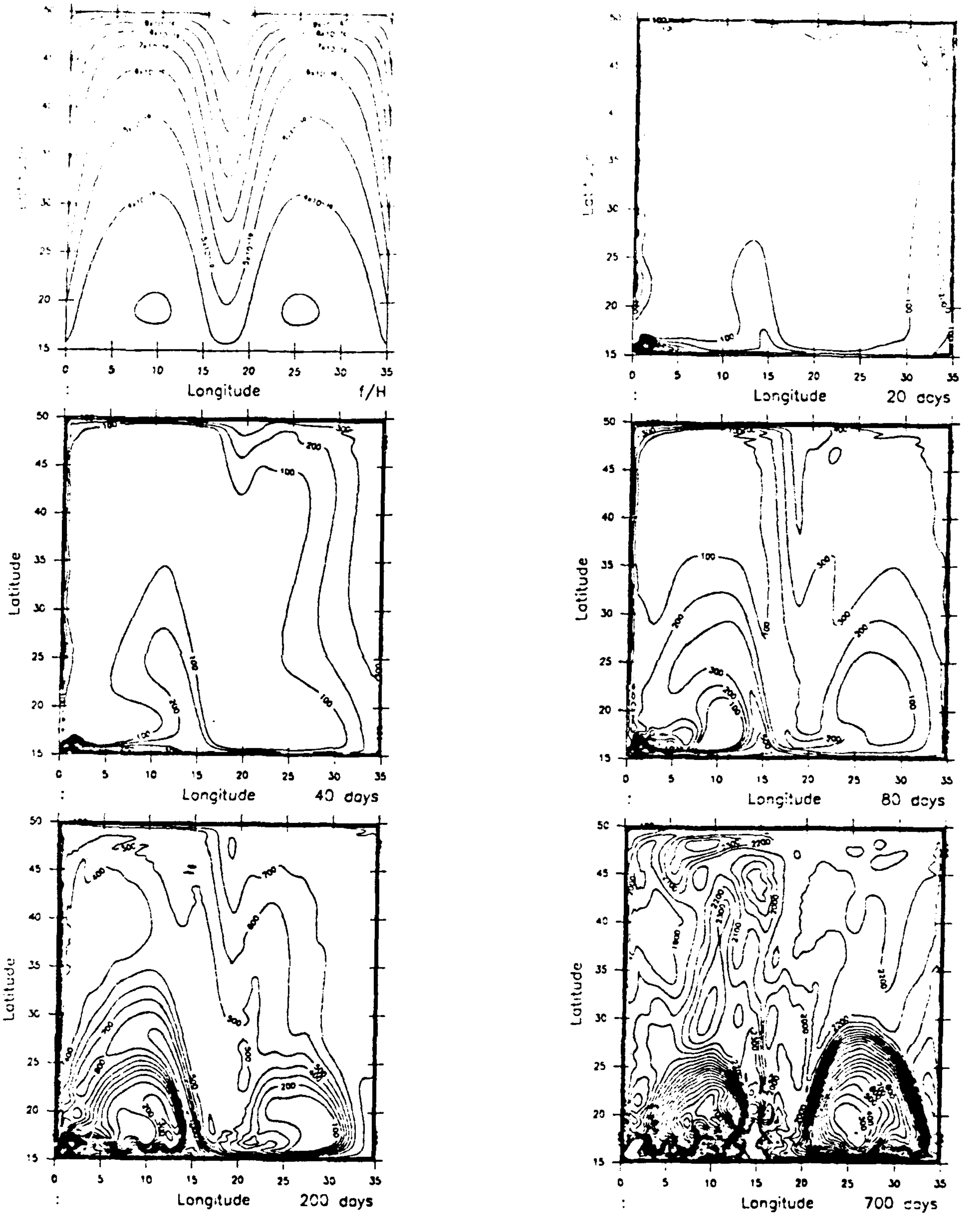

Figure 9. Geostrophic contours (f/H, in (cm sec)$^{-1}$) and spin-up of circulation shown in terms of interface elevation η (in centimeters) in a numerical calculation simulating a laboratory model of abyssal basin with a north south ridge in the middle and inflow at the southwestern corner. From Condie and Kawase (1992).

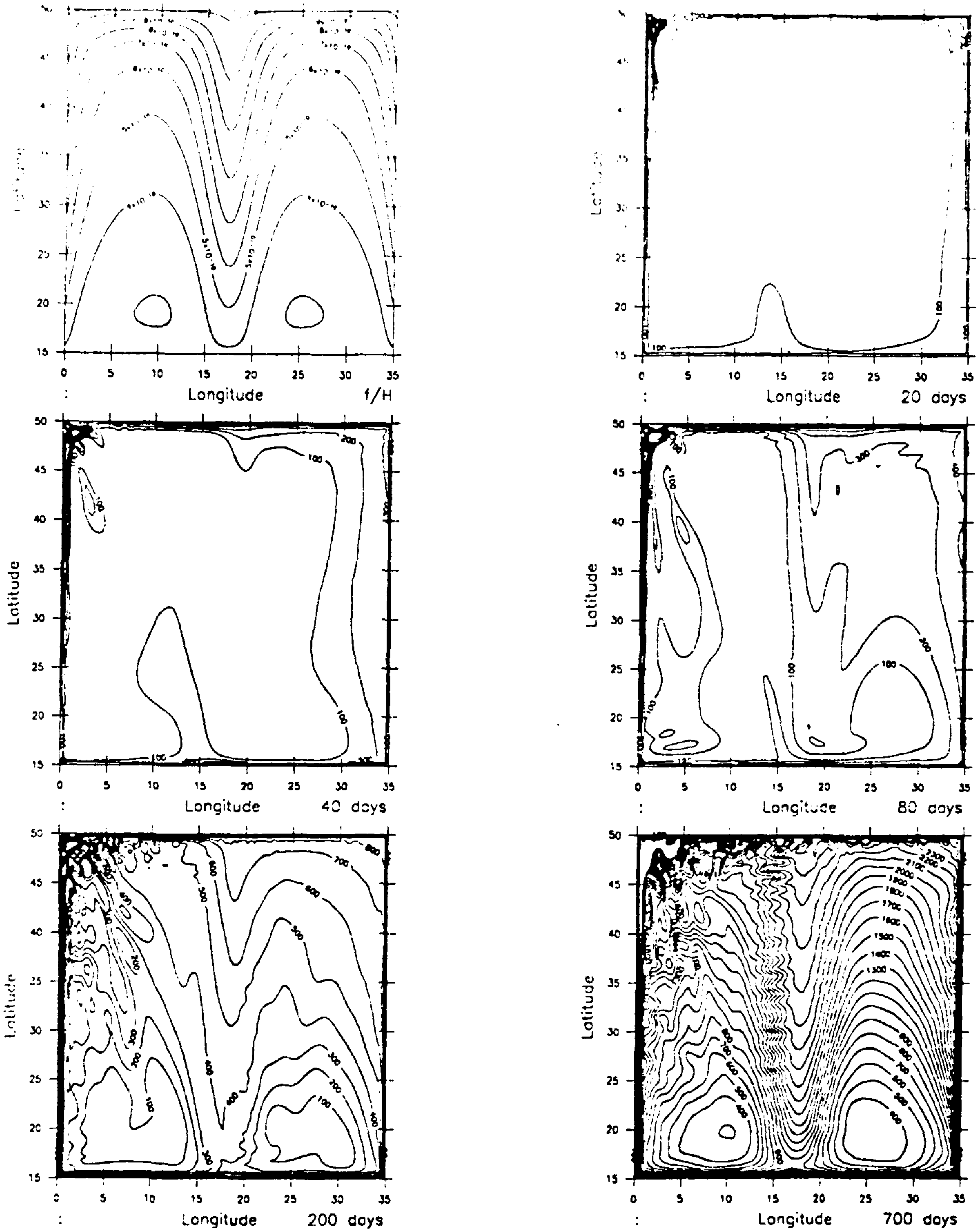

Figure 10. As in Figure 9, but inflow is on the northwestern corner. From Condie and Kawase (1992).